Geospace Environment Simulator

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Geospace Environment Simulator Project Team

We use three different simulation codes to model the geospace environment surrounding the Earth, i.e., an electromagnetic particle code, a hybrid code, and an MHD code. We have optimized these codes for the Earth Simulator (ES). We used both HPF/JA (High Performance Fortran by Japanese HPF Association) and MPI (Message Passing Interface) to implement parallel computation for the multi-node system on the ES. One of the major achievements of the initial effort to implement the electromagnetic particle and hybrid codes on the ES is development of a new algorithm for computation of particle moments such as charge density and current density by vector processors. The new algorithm enables us to use a large number of nodes even with the simple method of particle memory decomposition. In the MHD code we found that the HPF/JA can achieve a very high computational efficiency comparable to the manual parallel programming with MPI.

Keywords: geospace, plasma, particle code, hybrid code, MHD code, space station, spacecraft, space environment, vector computation, parallel computation, HPF, MPI

1. Introduction

The geospace is the space surrounding the Earth, where the electromagnetic dynamics of space plasmas plays dominant roles. Space stations such as solar power satellites in the future and other spacecraft composed of conducting materials are greatly influenced by dynamic variation of the ambient space plasma environment. The geospace environment is also greatly influenced by the solar wind plasma and the interplanetary magnetic field flowing from the sun. We reproduce various physical processes occurring in the geospace, such as formation of shocks, discontinuities and current layers, acceleration of particles, magnetic reconnection, and excitation of electrostatic and electromagnetic waves in association with dynamics of the whole magnetosphere due to variation of solar wind conditions. Depending on different spatial scales and time periods of the magnetospheric phenomena, we have to apply the electromagnetic particle code, hybrid code or MHD code to realistic three-dimensional models. The electromagnetic particle code solves motions of individual electrons and ions along with Maxwell's equations. The hybrid code treats electrons as a massless fluid, while solving motions of ions. The MHD code treats the plasma as a single fluid described by magneto-hydro dynamics. The database of three-dimensional models contributes to better understanding of the fundamental processes of the magnetosphere, designs of future satellite projects, and estimation of electromagnetic environment for utilization of the geospace.

2. Electromagnetic particle code (EM code)

The electromagnetic particle code solves the Maxwell's equations and equation of motion. Maxwell's equations are solved with leap-frog scheme and the equation of motion of each particle is solved with Buneman-Boris method. The objectives of the EM particle simulator in FY 2002 were:

A) Establishing fundamental concept of the EM particle code as a part of geospace environment simulator
B) Clarifying the interface between 3D orthogonal-grid EM code and the spacecraft simulator
C) Tuning 3D orthogonal-grid EM particle code for the ES.
D) Testing above code on the ES

As a concept of the simulator, the EM code consists of two major parts. One is an orthogonal-grid code and the other is a non-orthogonal grid code. The orthogonal-grid EM code (OEM) has been successfully transplanted to the ES system. A couple of versions, such as MPI, HPF and C++, are tested. The MPI version of the EM code achieves the best performance on the ES for now. At the time in the end of FY2002, 96.3% of Vector ratio has been recorded. The parallelization efficiency of 0.975384 has been achieved.

Multi-node simulation, up to 8 nodes, has been tested by MPI version of the 3D EM code. Energy conservation and plasma normal mode analyses have been made. Analyzing tools and data distribution methods are simultaneously developed in the EM.

Major problems which we are facing are;

A) Data transfer among the EM codes developers
B) Poisson equation solver for multi-node model
C) Parameter exchange with the hybrid/MHD codes

These problems are to be solved through further discussions and code modifications among the team members in the near future.

3. Hybrid code

The hybrid code is used for the study of low frequency electromagnetic phenomena on ion time and spatial scales in space, where one or more ion species are treated kinetically via standard PIC methods and the electrons are treated as a single charge neutralizing massless fluid. This will be able to provide the more accurate knowledge of space environment to give the technical guide for the satellites, the manned space stations, and the other future space development. The 20-25 % of failures and anomalies of spacecraft are attributed to space environment. Recently the larger scale integrated electronic circuit devises become to be installed in spacecraft but they are more sensitive to the space environment. Therefore we should investigate the followings via the hybrid simulations.

A) The interaction of ion thrusters as propulsion devices of satellites with the magnetospheric and interplanetary plasmas.
B) The magnetospherical global kinetic activity governing the enhancement of the high energy electrons in the radiation belt, which cause surface and internal spacecraft charging.
C) The appearance of high energy ions around the spacecraft from cosmic rays, solar flares, interplanetary shocks of CMEs, etc., which cause single event upsets and/or latch-ups on the electric circuits.

One of the major achievements of the initial effort to implement the hybrid code on the ES is development of a new method for computation of the particle moments on the spatial grid points by vector processors. We finished optimization of one-dimensional MPI hybrid code and tested the ability of list-vector (LISTVEC) operation for the effective memory-saved vectorization. The code has already achieved a good performance on 10 nodes of ES as shown in Figure 1. Its vector operation rate is 99.3[%], and its parallelization efficiency is 99.6[%]. We are now turning three-dimensional HPF orthogonal-grid and MPI body fitted coordinate hybrid codes.

In the standard plasma PIC code, a key point of optimization is how the density and currents are accumulated on the grids from the distributed particles because it occupies the most of the CPU times. One of the simple and robust methods of effective vectorization is to use a large memory buffer array for the density and current accumulation on each node without any fear of dependencies. However, since the memory size for the buffer is limited, this optimization is unsuitable for the large-grid-number simulation. In order to overcome this limitation, we tested the ability of list vector (LISTVEC) operation that dose not need the memory buffer. The original algorithm required a substantial amount of memory as a workspace for vector operation. Since the vector computation on the ES can achieve the maximum efficiency with the vector length of 256, the memory buffer of NGRID x 256 array was necessary for computation of one of the elements of the current density vector, where NGRID is the size of grid points representing the spatial dimension of the simulation model. On the other hand, the new algorithm only requires a much smaller number of arrays consisting of 256 elements compared with the number of grid points NGRID. The speed of the program using LISTVEC operation is closely related with the distribution of the particles on the memory array. However, it is, in some cases, faster and, even in the worst cases, is just twice slower than the common program.

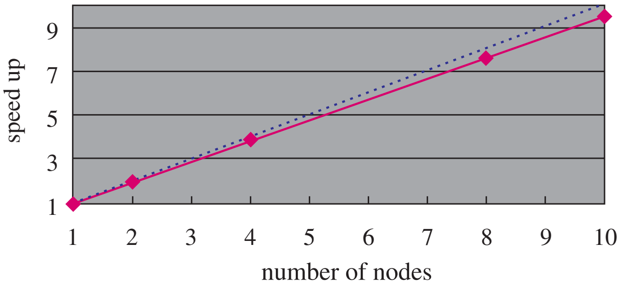

Fig. 1 Performance of one-dimensional hybrid code with MPI parallel programming on the ES.

With the new algorithm to perform vector operation for the current density computation with minimum memory, we can assign a large number of grid points for the field variables defining the simulation system. This enables us to use the particle memory decomposition for parallel computation. The particle memory decomposition can be implemented by making use of the HPF and MPI libraries.

4. MHD code

The MHD (magnetohydrodynamics) model treats the plasma as a single fluid described by MHD and Maxwell's equations. It can be directly applied to any scale of system because the three characteristics composed of fast magnetosonic wave, Alfven wave and slow magnetosonic wave are straight lines and have no dispersion effect. Therefore, it has been often used to model the whole Earth's magnetosphere. The MHD code simulation is necessary for defining the boundary conditions for the hybrid codes and the electromagnetic particle codes for smaller scales.

The three-dimensional global MHD simulation code for the interaction between the solar wind and the Earth's magnetosphere solves the MHD and Maxwell's equations in three-dimensional Cartesian coordinates (x, y, z) as an initial and boundary value problem using a modified leap-frog method. The MHD quantities are decomposed in the z-direction in HPF/JA (High Performance Fortran by Japanese HPF Association) and MPI (Message Passing Interface) for parallel computation. The MHD codes, which are fully vectorized and fully parallelized in HPF/JA and MPI by using Fujitsu VPP5000, were tested to find how good efficiency they can achieve by more large number of processors in Earth Simulator (ES) and how they need to be improved to achieve higher efficiency, before the MHD codes will be applied to the practical problems for better understanding of the fundamental magnetospheric processes and estimation of electromagnetic environment for utilization of geospace.

For the first time, the original MHD codes for HPF and MPI, which were efficiently executed on Fujitsu VPP5000, were performed on the ES. In the models, a directive "reflect" is used for communication among decomposed domains in the z-direction in HPF/JA, on the other hand "mpi_send" and "mpi_recv" are done in MPI, and the wild card, "MPI_PROC_NULL" was not used. As a result, the MPI code relatively shows a slower speed for a larger number of processors, while the HPF/JA code shows a good scalability as shown in the left panel of Figure 2. We have tried to improve the MPI MHD code by introducing the wild card, "MPI_PROC_NULL" and moving "if sentence" outside of "do loop". Thus the improved MHD code could present a good performance and a good scalability for a large number of processors on the ES as shown in the right panel of Figure 2.

We are planning to introduce a multi space-time method in the three-dimensional MHD model to simulate the inner magnetosphere as well as the outer magnetosphere with higher spatial resolution and also to adopt an inhomogeneous grid system to solve consistently the three-dimensional magnetosphere-ionosphere coupling process by using an extended MHD equation with the generalized Ohm's law.

5. Conclusion

We have achieved a high rate of vectorization in the electromagnetic particle code, hybrid code and MHD code. We have found an effective algorithm to compute particle moments at the grid points from particle quantities without the memory buffer for vector computation. These three codes have been modified for parallel computation based on the MPI and HPF/JA libraries. The efficiencies of the vector/parallel computations are high enough to allow us to use a large number of nodes of the ES.

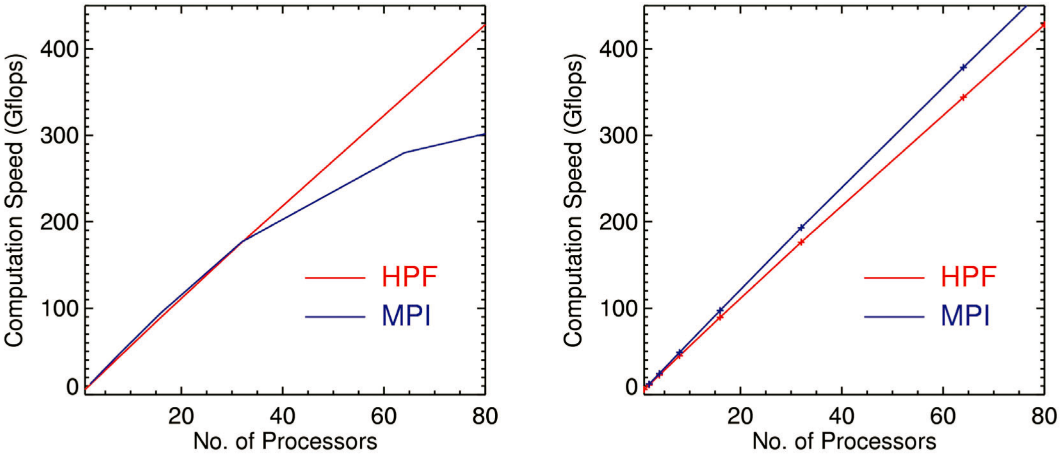

Fig. 2 Performance of the original MHD code without MPI_PROC_NULL (left panel) and the improved MHD code with MPI_PROC_NULL (right panel) in the ES (Earth Simulator), where vectorization efficiency is 99.7-99.8%, parallelization efficiency, 99.92-99.94% and the available number of processors is 1245 for HPF and 1644 for MPI.

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地球周辺の宇宙空間の宇宙ステーションや衛星の電磁プラズマ環境を定量評価する宇宙環境シミュレータのプロトタイプを構築するために、電磁粒子コード、ハイブリッドコード、MHDコードの3つを地球シミュレータに移植した。ベクトル計算およびマルチノード並列計算を行うために、HPF／JAとMPIを使った2通りの方法によって最適化プログラミングを行った。粒子およびハイブリッドコードの電荷密度・電流密度の計算においては、大きな作業配列を必要する従来のベクトル計算の方法を改善して、新しいベクトル計算アルゴリズムを開発した。これによりノード毎に十分な数の格子点を確保して、プログラムの簡単な粒子メモリ分割による並列計算が可能になった。MHDコードでは、HPF版コードの実行速度がMPI版コードに匹敵することがわかり、HPFの有用性を確認した。各コードにおいて10ノードでの高効率のベクトル・並列計算に成功し、100ノードを越える大規模計算を実行する用意が整った。

キーワード：宇宙、プラズマ、MHD、粒子コード、ハイブリッドコード、宇宙ステーション、宇宙機、宇宙環境、ベクトル計算、並列計算、HPF、MPI